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MARS HUMAN EXPLORATION SCIENCE STRATEGY

Report of the Ames Space Science Division Mars Study Project

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Report of the Mars Science Workshop
NASA Ames Research Center
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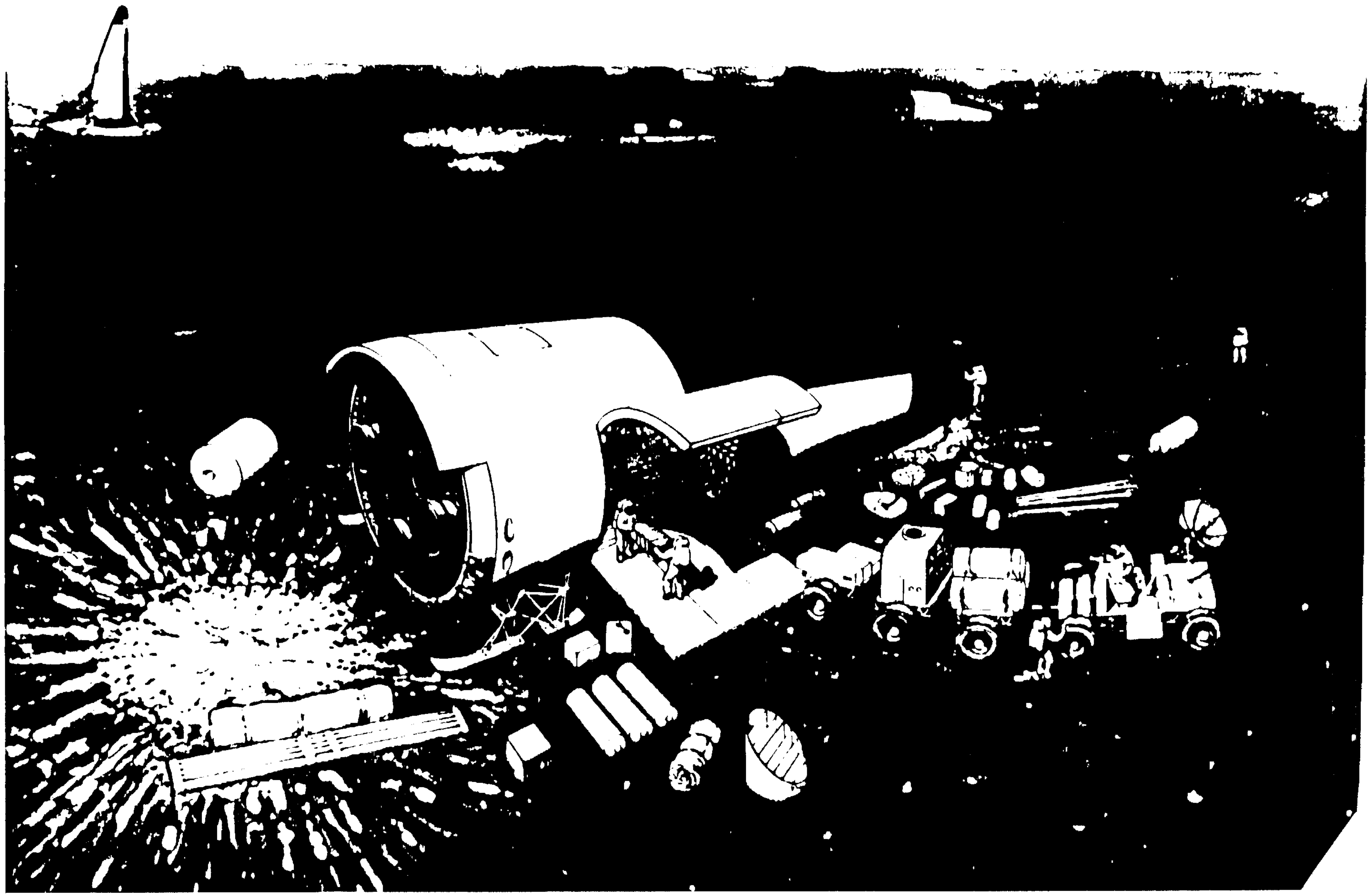
Compiled by:

C.R. Stoker, C.P. McKay, R.M. Haberle
Space Science Division
NASA-Ames Research Center

D.T. Andersen
Lockheed, NASA-HQ

Frontispiece: Artists concept of human landing on Mars, by C. Emmart



EXECUTIVE SUMMARY KEY POINTS

- **Scientific Objectives:**

  Planetary Evolution, Climate Change, and Life
  - Life Search
  - Climate History
  - Geological History

  Human Habitability of Mars
  - Medical
  - Human Factors
  - Resources

- **Phases of Human Exploration**

  Precursor
  - Provide the information needed to plan human missions
  - Identify and characterize landing sites

  Emplacement Phase
  - Several small, initial human missions with short stay times
  - Local investigation of a few regions

  Consolidation Phase
  - Beginning of continued human presence and resource utilization
  - Scientific exploration of a region of Mars (Coprates Quadrangle)

  Utilization Phase
  - Permanent, self sufficient base
  - Detailed, global, scientific exploration

- **Site Selection**
  - Must be viewed in a 30+ year time frame
  - Critical for life search; possible paleolake sites under investigation
  - Suggested regional area: Coprates Quadrangle and adjacent regions
    - provides an area where compelling scientific issues can be addressed over a decades-long program.

- **Resource Utilization**

  Critical for permanent presence

- **Mobility**

  Local Lunar rover-like vehicle in emplacement phase
  Pressurized vehicle in consolidation phase
  Global point-to-point vehicle in utilization phase

- **Teleoperation and Telepresence**

  Critical for extending human range and capabilities on Mars (and the Moon; lunar derived technology will be useful)
  - Local teleoperated rover in emplacement phase
  - Satellite controlled rovers over regional site in consolidation phase
  - Satellite-relay controlled teleoperations over entire globe in utilization phase

EXECUTIVE SUMMARY

The scientific objectives of Mars exploration can be framed within two overarching themes: 1) Planetary evolution, climate change, and life; 2) Human habitability of Mars. Within these themes, we examined the exploration objectives for the fields of exobiology, climate and atmosphere, and geology. Human exploration will proceed in four major phases: 1) Precursor missions to obtain environmental knowledge necessary for human exploration; 2) emplacement phase missions including the first few human missions in which humans will explore the local area of the landing site; 3) consolidation phase missions which will begin permanent base build up and crews will be capable of detailed exploration over regional scales; 4) utilization phase, in which a continuously occupied permanent Mars base exists, and humans will be capable of detailed global exploration of the martian surface. Site selection for human missions to Mars must consider the 30+ year time frame of these four phases. We suggest that operations in the first two phases be focused in the regional area containing the Coprates Quadrangle and adjacent areas. The key question for human habitability of Mars is whether martian resources can be used to support a permanent human presence. Evaluating the location and accessibility of key resources, particularly water, will be an important science objective for all phases of exploration. The phases of human exploration differ primarily in the range and capabilities of human mobility. In the emplacement phase, an unpressurized rover, similar to the Apollo lunar rover, will be used and the range will be limited by the duration of the space suit life support system. In the consolidation phase, mobility will be via a pressurized all-terrain vehicle capable of two week expeditions from the base site. In the utilization phase, humans will be capable of 90 day long expeditions to any point on the surface of Mars using a suborbital rocket equipped with habitat, lab, and return vehicle. Because of human mobility limitations, it is important to extend the range and duration of exploration in all phases by using teleoperated rover vehicles. Local teleoperated rovers operated within line of sight of the landing site can be used in the emplacement phase to extend human exploration range to the 100 km scale. Satellite controlled teleoperated rovers will help humans to explore Mars in the later phases.

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BACKGROUND

This document is the result of a several month effort at NASA Ames Research Center devoted to defining the science objectives and overall strategy for human exploration of Mars. This effort was funded by the Office of Exploration (Code Z) under the auspices of Dr. Carl Pilcher, Director for Science. As part of this effort, a workshop was held 30—31 August, 1989 at NASA Ames to discuss science and human exploration of Mars. A list of workshop participants is included at the end of this report.

Wherever possible we have tried to keep this report consistent with the approach taken in the companion studies done for Lunar Bases and with the Mission Analysis and System Engineering (MASE) studies for Lunar and Martian exploration. For example, the use of emplacement, consolidation, and utilization phases reflects terminology developed by these groups. This report has benefited from information on Lunar Bases provided by Michael B. Duke and on MASE studies provided by Nancy Ann Budden.

This report was edited by C.R. Stoker, C.P. McKay, R.M. Haberle, and D.T. Andersen. Major contributions of text and concepts were made by O. Gwynne, D. Schwartz, R. Kahn, M. Carr, S. Squyres, J. Marshall, T. Roush, A. Zent , J. Pollack, and N.A. Budden.

I. SCIENTIFIC THEMES FOR HUMAN EXPLORATION OF MARS

• Planetary Evolution, Climate Change, & Life

The major elements of this theme are:

- **Search for Life (Past and Present)**
- **Climate History of Mars**
- **Geological History**

• Human Habitability of Mars

The major elements of this theme are:

- **Resources on Mars to support human exploration and settlement**
- **Medical issues**
- **Human Factors**

SCIENTIFIC THEMES FOR HUMAN EXPLORATION OF MARS

Human exploration of Mars provides unique opportunities to conduct an in-depth scientific study of that planet. Human presence opens up new possibilities in the scope and detail of scientific exploration. There will be a phased approach to exploration in which the range of mobility and scientific capability progressively expands. Science objectives for human exploration must be consistent with the requirement for sustained scientific commitment over 30+ year time frames. Two overarching scientific themes for human exploration of Mars are: 1) Planetary evolution, climate change, and life, and 2) Human habitability of Mars.

The theme of Planetary evolution and life deals with understanding the evolution of the terrestrial planets and the role that life plays in that evolution. Clearly, Mars and Earth have had very different biological histories. If Mars is without life, present or past, then it represents a stark contrast to the Earth which has been influenced by life from very early in its history. If the early environment of Mars was conducive to the origin of life then the comparison of this early period with the early Earth would be compelling. In addition, understanding what caused the climate of Mars to change will help us to understand global climate change on Earth. In order to understand planetary evolution, with or without the presence of life, the climatic history and geological record of Mars must be investigated. Mars provides a natural laboratory, for the study of planetary evolution, both in terms of its present processes and the record of its past environments. The major elements of this theme are thus: 1) Search for Life (Past and Present), 2) Climate History of Mars, and 3) Geological History.

The theme of Human habitability of Mars deals with the potential of that planet to be the site of significant human activity and possibly long term exploration. The fact that Mars appears to have resources needed to support humans living on its surface and it may be possible to locate, extract, and utilize them, make this option available. There are driving scientific questions dealing with the medical and psychological factors associated with living and working on Mars. The elements of this theme are thus: 1) Resources on Mars to support human exploration, 2) Medical issues, and 3) Human Factors.

ELEMENTS OF MARS EXPLORATION

Phase	Dates	Notes
Precursor	1965-2016	• Obtain Environmental knowledge necessary for human exploration • Identify and characterize sites
Emplacement	2016-2024	**CHARACTERISTICS** • First few human missions • Human landings at several sites • Limited human mobility (10 km) • No resource utilization • Small crew (~ 5) • Short stays (~30 days) • Lander is habitat **ACTIVITIES** • Local exploration by humans • Teleoperated "fetch" rovers over 100 km range • Sample collection, limited analysis
Consolidation	2024-2034	**CHARACTERISTICS** • Crew overlap • Begin resource utilization • Base construction underway **ACTIVITIES** • Expeditions in pressurized rover over 100 km range • Teleoperation/presence over regional distances • Extensive sample analysis
Utilization	2030 —>	**CHARACTERISTICS** • Permanent base • Self sufficiency • Global point-to-point access **ACTIVITIES** • Spawning "Emplacement Phase" remote bases • Global scale telepresence with sample return to base • Complete capability for sample analysis

FOUR PHASES OF MARS EXPLORATION

The four major phases of martian exploration are shown in the table on the preceding page. In the Precursor Phase, robotic exploration of the planet is performed to obtain the environmental knowledge of Mars needed to enable safe human landings and operations on the surface of Mars and to maximize the science return from human missions. The precursor exploration phase essentially began when the first spacecraft was sent to Mars (Mariner 4; 1965), continues with missions currently underway, and ends with the first human landing.

The Emplacement Phase of Mars exploration includes the first few human missions to the surface of Mars. Such exploratory missions will go to several different sites (at least three sites should be explored before choosing a final base location). These missions will involve small crews that will spend approximately one month on the martian surface. The missions will be completely self contained in terms of life support and mobility capabilities. The crews will live in the lander vehicle for the duration of the mission. Human mobility (approximately 10 km) will be limited to the range allowed by the life support capability of a space suit and an unpressurized rover. Scientific activities will consist of local exploration within this range. In addition, the crews will be able to explore a larger area in the vicinity of the landing site using teleoperated rovers which will have a range of approximately 100 km and are capable of collecting samples and returning them to the lander area. These missions will have very limited sample analysis capability and will concentrate primarily on sample collection for return to Earth.

The Consolidation Phase of human exploration focuses on constructing and bringing to operational status a permanent base which uses martian resources to support the human crews. There will be several of these missions, involving medium-sized crews (approximately 15) with extended residence times on the martian surface (300-600 days). Continuous human presence on the surface of Mars begins during this phase. The scientific objectives of this phase will focus on regional exploration of the areas visited earlier by teleoperated rovers in the emplacement phase. Human exploration will be accomplished in a "winnebago" style pressurized rover which will sustain a crew for two weeks or more in excursions over rough terrain. In addition, the crew will teleoperate rover vehicles to explore specific sites within the "Primary Science Region" (see page 9). We assume that teleoperation of rovers will be possible within the footprint of a single geostationary satellite centered over the base location. Extensive sample analysis will be performed at the base site and only the most important samples will be selected for return to Earth.

The Utilization Phase of human exploration is characterized by the existence of a permanent base on Mars with a large resident staff. The global exploration of Mars will be accomplished via suborbital rocket powered vehicles capable of point-to-point hops to anywhere on the surface of Mars. These vehicles will be similar to the martian landers used in the emplacement phase of exploration (see page 39). Thus, this phase will spawn "emplacement phase-style" remote bases. A network of geostationary satellites will enable global access to the surface of Mars by way of a network of rover vehicles operated via telepresence, and capable of sample return to the main Mars base. During this phase, most sample analysis will be performed on Mars, with only minimal sample return to Earth. In addition to intensive investigation of sites all over the surface of Mars, a key scientific objective of this phase of exploration will be the analysis of the habitability of Mars by humans.

SITE SELECTION FOR HUMAN BASE

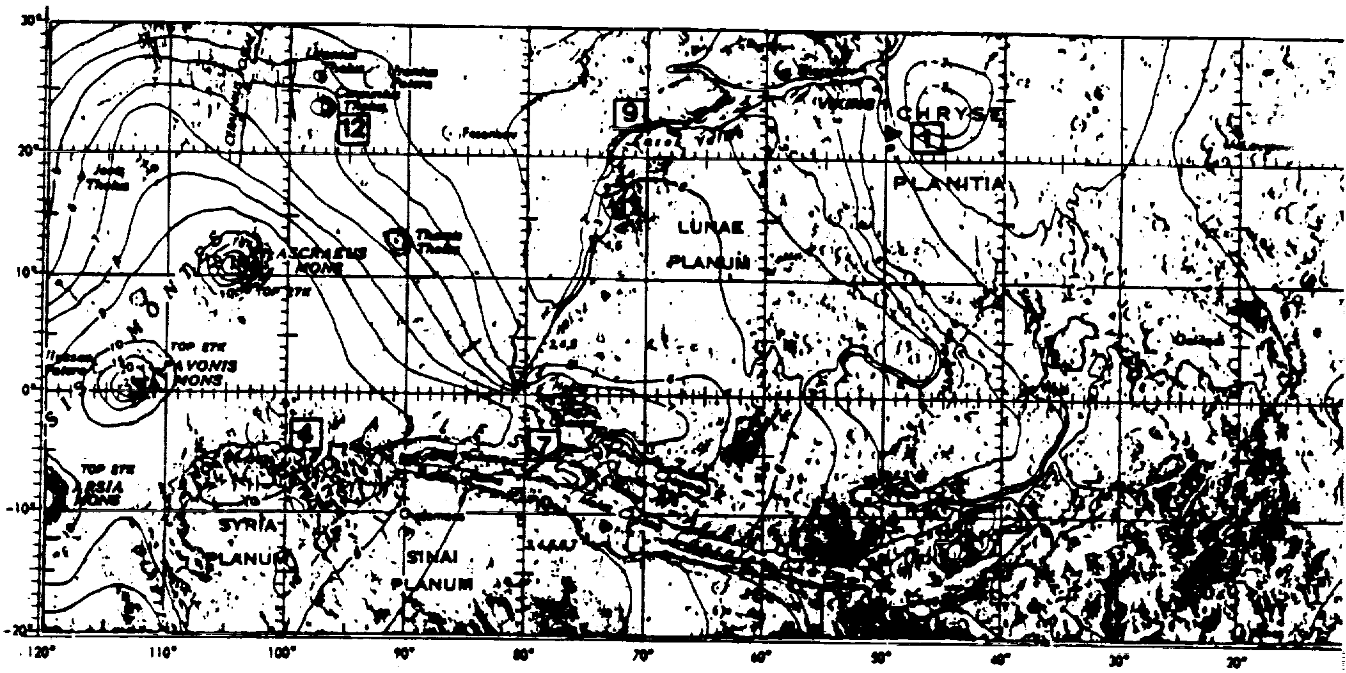


Figure 1. Proposed region of science exploration for human missions: Coprates Quadrangle Region.

SITE SELECTION FOR HUMAN BASE

The site selected for human exploration must satisfy two scientific requirements: 1. Proximity to areas of scientific interest suitable for human exploration during the emplacement phase. 2. Compelling and continuing scientific issues that can be addressed at the site in the consolidation phase of exploration.

There are many sites that can satisfy the first requirement as evidenced by the long list of interesting sites identified by the Mars Rover Sample Return (MRSR) science working group. Human exploration introduces a new dimension to site selection with the requirement that science activities of interest and merit be maintained during the period when human access is regional but not yet global. This phase could last for many decades. Thus, selection of a site for the permanent human base must be viewed regionally. We expect that, during the consolidation phase, the crew at the Mars outpost will have access, either directly or via teleoperated robots, to sites separated by distances of several thousand kilometers.

With these constraints in mind, we suggest that the region containing the Coprates Quadrangle and adjacent areas should be the site of the human base on Mars. We propose this region (shown on the facing page) as the primary science region, too. Included in this region are: 1) Tharsis volcanoes; 2) Valles Marineris; 3) the ancient cratered terrain of the Margaritifer Sinus region, containing a possible paleolake site; 4) Kasei Vallis, site of runoff channels; 5) the region northwest of Valles Marineris containing numerous outflow channels; 6) The northern plains in the vicinity of Chryse; and last but not least, 7) The Viking 1 landing site. This collection of fundamentally interesting areas (plus any other discoveries of interesting sites) would provide a compelling and continued harvest of scientific return from Mars that would befit a human exploration effort.

We have identified three possible locations within this regional area that could serve as the sites of one or more bases during the Emplacement Phase of human exploration. Each site has high scientific interest. These sites are A) Kasei Vallis, B) Candor Chasma, and C) Paleolake site in Margaritifer Sinus. During the consolidation phase, one of these sites would become the main base while the others could be maintained as remote field outposts.

II. PLANETARY EVOLUTION AND LIFE

SEARCH FOR LIFE (PAST OR PRESENT)

Prioritization for life search

Type of life search (Priority)	Probability of Success	Level of interest
Search for evidence of chemical evolution and any organic material (High Priority)	High, follows directly observations of liquid water in early epoch	Strong scientific interest
Search for fossil and chemical evidence of past life (High Priority)	Possible, depending on the time over which liquid water persisted	Strong scientific and general interest
Search for present life in specialized habitats (Low Priority)	Speculative, no basis for supposing extant life	Fundamental and broad scientific and public interest

- **Sites for searching for past life**
  - Sites of past bodies of standing water (paleolakes)
  - Hydrothermal sites and/or springs
  - Sites of periodic liquid water activity such as runoff channels and source regions in the chaotic terrain

SEARCH FOR LIFE (PAST OR PRESENT)

PRESENT LIFE: Currently there is no indication that there is extant life on Mars nor does the current climate appear hospitable towards life. However, the scientific question of extant life on Mars is closely associated with the policy issues of forward and back contamination. Therefore it is expected that precursor activities dealing with planetary protection issues will address the existence of extant life. If definite evidence for life is found this will have a significant impact on the planning for human exploration. If the precursor program supports what current scientific indications suggest, no indication that there is any extant life on Mars, then it is unlikely that the search for extant life will be a major science driver of the human exploration mission. However, extant life will be difficult to rule out completely and there will be continued interest in testing samples and examining sites for the presence of living forms, however low the probability of success.

PAST LIFE: There is considerable geological evidence that Mars had liquid water on its surface at one time. Liquid water is the essential requirement for life and the possibility exists that life originated on Mars during a warm, wet, early period. More so than the other aspects of the science to be conducted by human explorers, the search for evidence of past life will be dependent on choosing the sites to be investigated. The key requirement is finding sites where there may have been biological activity in the past and where a chemical or morphological record of postulated activity has been recorded. This implies the frequent or persistent existence of liquid water. Possible candidate sites include: Sites of past bodies of standing water (paleolakes), hydrothermal sites and/or springs, sites of periodic liquid water activity, such as runoff channels.

Of this list, the first two represent sites of significant potential in terms of supporting biological activity and leaving a record of it. Currently no hydrothermal or spring sites on Mars have been identified but geological features suggests that these could have been prevalent in the past (but may be absent in the present epoch).

STRATEGY FOR FOSSIL-LIFE SEARCH

- **Precursor Phase**

  - Locate sites of biological interest with remote sensing data
    - Paleolakes, Hydrothermal sites and springs, Sites of episodic water activity
  - Verify via *in-situ* measurements that the target sites had liquid water habitats suitable for life
  - Search for organic material below the surface
  - Characterize the proposed soil oxidant and its role in organic destruction
  - Sample collection for detailed analysis on Earth

- **Emplacement Phase**

  - Direct and teleoperated investigation of local sites (assuming base is located near a paleolake site, for example)
  - Sample collection from local sites via teleoperated vehicles

- **Consolidation Phase**

  - Intensive investigation of sites on regional scale likely to have been sites for past life
  - Capability to do sample analysis on site
    Microscopy
    Elemental Analysis (e.g., X ray florescense spec. (XRF))
    Organic and Mineralogical Analysis (e.g; Differential scanning calorimeter/evolved gas analyzer (DSC/EGA))
  - Sample collection and analysis used to guide further field work making use of human capabilities

- **Utilization Phase**

  - Sites investigated on global scale
  - Complete sample analysis capability at Mars Base
    Microscopy
    Elemental Analysis (e.g., XRF)
    Organic and Mineralogical Analysis (e.g, DSC/EGA)
    Electron microscopy
    Stable isotope analysis
    Microprobe analysis

STRATEGY FOR FOSSIL-LIFE SEARCH

Description

Since the geologic history of the site investigated for past evidence of life is critical to the possibilities of success of such an investigation, it is necessary to be quite certain that the site is indeed a (e.g.) paleolake site. This identification and certification of sites would be accomplished with the precursor missions. In general, remote sensing data will be required to identify sites. On the Mars Observer, the information on topography, mineralogy (TES), and images will be of use in locating paleolake sites. Direct confirmation with *in-situ* analysis on a rover or via a sample return would be necessary to confirm the geological models of the sites developed by the remotely sensed data.

The role of humans in the field will be to collect samples and analyze them on site with the analytic capability available (very little in the emplacement phase, moderate level in the consolidation phase, and essentially complete capability in the utilization phase). Then based upon these results, more samples are collected, etc. This feedback between the collection, analysis and subsequent investigation of the site make use of the unique capabilities that humans can bring to the scientific exploration of Mars. Human intelligence and adaptability in field studies is critical to the life search as is the ability to do sample analysis quickly, which suggests a fairly complete analytical capability on Mars (as indicated in the chart).

EXAMPLE SITE FOR LIFE SEARCH

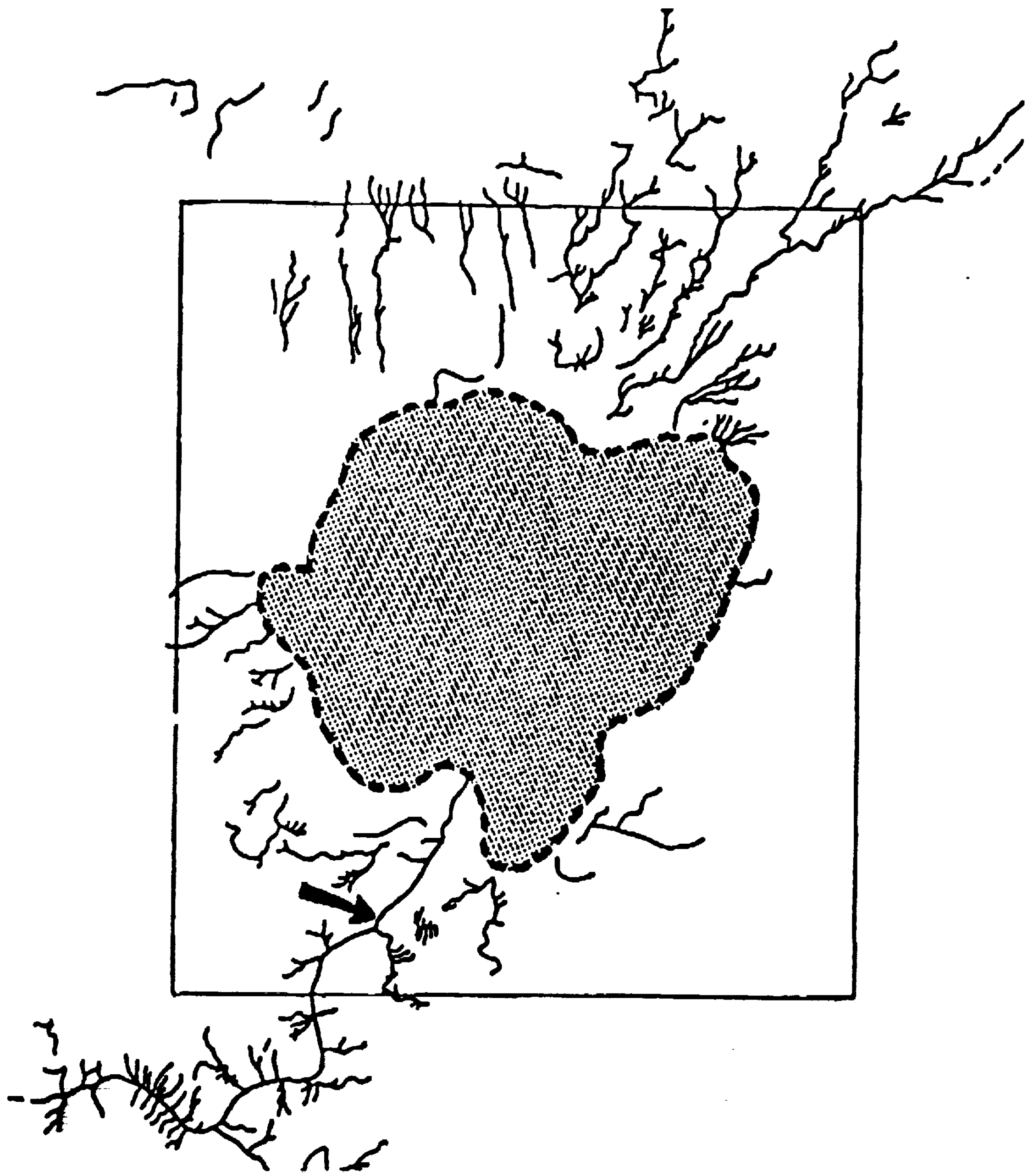


Figure 2. Geologic map of ancient valley system and possible paleolake

EXAMPLE SITE FOR LIFE SEARCH

Map 1: Provided by S. Squyres

- Site is covered by Viking orbiter images 651A92 and 94. Best resolution is approximately 260 m/pixel.

- Site is at latitude -22°, longitude 12°, in the Margaritifer Sinus region. This is site 2 in the MRSR Mars Landing Site Catalog.

- Map shows a network of ancient valley systems flowing into a local depression in the heavily cratered highlands of the Margaritifer Sinus area. The boundaries of the depression are indicated by the shading. Only one valley, indicated by the arrow, flows out of the depression. This configuration of valleys suggests that the depression was partially filled with water from the in-flowing valley systems, spilled over a divide, and eventually drained. As the water that eroded the valleys emptied into the depression, it would have lost its carrying capacity and deposited its load as sediments within the depression. A particularly interesting characteristic of the material in the interior of the depression is that it has an unusual hummocky appearance. The origin of this topography is unclear; one possibility is that it is due to freeze-thaw processes in water-saturated sediments.

The scale across the depression is about 150 km.

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Key Science Questions

1. Was there an early dense atmosphere on Mars?

- What was the nature and composition of the early atmosphere?
- For how long and by what mechanisms was any early dense atmosphere maintained?
- Where did those volatiles go?

2. What processes have been responsible for atmospheric evolution over time?

- What is the nature and distribution of the present volatile reservoirs on Mars?
- What processes have controlled the state and distribution of near-surface reservoirs?
- What mechanisms dominate the depletion of atmospheric gases?

3. What aspects of the current climate of Mars can be useful as a key to the past?

- Has there been cyclic climatic change?
- What are the present cycles of water, dust, and CO_2 on Mars?
- What exogenic and endogenic processes control the current climate of Mars?

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

A key objective of atmospheric sciences research on Mars is to study the evolution of the martian atmosphere over time, and the physical processes responsible for climate change, both past and present.

Major questions include the early state of the atmosphere as well as recent climate cycles and annual transport of water, sediment and CO_2. Mars geology indicates major climate changes have occurred on Mars. The occurrence of valley networks and other fluvial features on ancient terrains suggests Mars may have had a dense atmosphere early in its history. The layered terrains that characterize both polar regions could be the result of succession of ice ages during more recent times. When viewed in conjunction with Earth, Mars offers an opportunity to help separate exogenic processes (such as variations in solar radiation) from endogenic ones (like volcanic eruptions) as factors that affected climate through Mars history.

The strategy for obtaining climate history constraints is to obtain data on the current state of the martian surface and atmosphere. Once the mean state of the Mars atmosphere, climate, and its interannual variation are understood, along with real-time physical processes, we can generate models that reconstruct how processes operated in the past to moderate and change martian climate.

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Precursor science

- **Orbiter science**
  - Infrared atmospheric soundings (temperature, dust, water vapor, clouds)
  - Wind sensors (circulation patterns)
  - Aeronomy measurements (escape processes)
  - Synoptic imaging (circulation patterns, dust storms, polar cap behavior, surface dust deposits)
  - Electromagnetic sounding (internal structure, layered terrain, permafrost)
  - Multispectral near infrared spectroscopy (surface composition)

- **Network science**
  - Surface physical characteristics
  - Surface meteorology
  - Elemental abundances
  - Crude surface mineralogy

- **Sophisticated Moving Automated Laboratory (Rover)**
  - Close-range EM sounding
  - Mineralogy
  - Crude petrology
  - Crude age dating
  - Rock sample volatile analysis

- **Sample Return**
  - Sophisticated chemical analysis, petrology, absolute ages
  - Surface sampling of water-lain sediments
  - Atmospheric gas and aerosol samples
  - Cores from polar layered terrain
  - Impact breccia of different ages containing trapped gases.

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Precursor Science

In this phase of exploration we will systematically build up our understanding of the Martian surface and atmosphere. The goal is to establish a climate baseline before human exploration begins, and to optimize site selection for meeting the science objectives. Therefore, it is important that a planetary observing system for monitoring Mars weather and climate also be built up during this phase. Every opportunity to emplace surface meteorological stations should be taken, and every effort should be made to ensure continuous monitoring from orbit. Ultimately, the integration of orbiter, network, possibly balloon, and rover observations will be achieved during this phase. Interdisciplinary studies oriented toward understanding the dust, water, and CO_2 cycles, as well as the general circulation should be undertaken. Since the central issue here (characterizing volatile reservoirs) is also the central lunar resource issue, there should be some common heritage.

Each mission in the precursor phase will guide its follow-on. Remote sensing of the atmosphere and surface from orbit can establish the basic structure of atmospheric circulation patterns and map the surface composition and geologic units that can help identify candidate carbonate sediments and volatile reservoirs. A network of surface stations (e.g. penetrators) can then provide in-situ measurements needed for ground truth of the remote sensing data, and further narrow the search for suitable sample return sites. A global meteorological network would also provide the basis for weather forecasting. Rovers on the surface will be capable of more sophisticated analyses and can obtain samples from multiple units which can help establish evolutionary processes. Returned samples, however, are necessary to establish more precise mineralogy and age dating.

Note that since precursor missions relevant to these studies are already under development or being built (MO, Mars 94), and there are needs for instrument development for follow-on, but relatively near-term missions, it is essential now to take the steps required to optimize these missions as precursors.

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Emplacement Phase

- **Erect local meteorological network (operational and science)**

- **Tie into global meteorological network (operational and science)**

- **Human and teleoperated sample collection of materials recording past climate condition**

  - sediments, including waterlain sediments. e.g., carbonates, nitrates, evaporites

  - impact breccias containing trapped gases

  - rocks containing cosmic ray exposure record

  - rocks that record early weathering processes

- **Identification and characterization (via rover) of sites that will be investigated by humans in later phases**

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Emplacement Phase

At each landing site during the Emplacement Phase, local meteorological networks will be deployed. These will define site climatology and broaden the global observational data base. Environmental parameters to be measured are wind, temperature, pressure, atmospheric dust loading and humidity. The crew can monitor global weather activity by tieing into the existing weather network established during the precursor phase. This will enhance their operational capability by providing real-time weather reports.

A major goal of this phase is the acquisition of suitable samples for return to Earth. This could be done directly by the crew or through teleoperated vehicles. Four types of samples could yield clues about Mars past climate: waterlain sediments may contain carbonates or other chemicals indicative of a dense early atmosphere; old impact breccias may contain actual samples of the early Martian atmosphere; certain rocks may provide information on the time evolution of the Martian atmosphere through analysis of their cosmic ray exposure record; others may yield clues about the early Martian environment through their weathering products. A better estimate of the current composition of the Martian atmosphere could be obtained by returning samples of the atmosphere itself.

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Consolidation Phase

- **Extend sample collection to sites within pressurized rover range**

- **Extensive analysis of samples on Mars**
  - elemental analysis (e.g. X-ray Alpha Proton Scattering)
  - stable isotope analysis (e.g. Mass spec. or Laser spec.)
  - mineralogical analysis (e.g. Differential Scanning Calorimeter-Evolved gas analyzer)
  - radio isotopic age dating

- **Identification and characterization (via rover) of sites that will be investigated by humans in later phases**

- **Enhance density of meteorological net for prediction (operational)**

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Consolidation Phase

The diversity of samples collected will be broadened during this phase. Regions not accessible in the emplacement phase, such as impact breccias or waterlain sediments, may now be accessible and should be explored for suitable samples. In addition, the crew will have more sophisticated on-site analysis capability. A variety of analysis can be carried out on the samples they acquire (elemental abundances, mineralogy, isotopic composition, etc.) at Mars rather than returning samples to Earth. However, samples should still be selected for return to Earth.

The density of meteorological stations should continue to be increased during this phase. This could be done during field trips away from base or by teleoperated vehicles.

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Utilization Phase

- **Human exploration and sample collection at polar regions**

- **Human exploration and sample collection from sites surveyed in consolidation phase**

- **Return of samples to permanent base for detailed analysis**

- **Telepresence rover exploration anywhere on Mars**

- **Field studies for intensive studies of meteorological events**

    - dust storms

    - cyclonic storm systems

- **Instruments for investigation of the polar caps and dust storm source regions**

ATMOSPHERIC SCIENCE AND CLIMATE HISTORY

Utilization Phase

Global mobility during this phase will permit the collection of samples from the polar regions which are each characterized by extensive layered deposits believed to be the result of cyclic climate changes during the recent past. Obtaining and preserving good cores or examining terrain facies directly may yield the Rosetta Stone of the Martian "Ice Ages". The composition and age of these terrains need to be determined as a function of depth. Global mobility will also enable sampling of regions previously found from orbiter measurements to be good carbonate reservoir sites, but not accessible during the emplacement or consolidation phase.

A variety of meteorological phenomena can be studied through field studies. Dust storm source regions can be instrumented to learn more about the conditions necessary for storm development and decay. The composition and behavior of the polar caps can be studied and monitored. The meteorological network is expanded with stations emplaced both by penetrators and manually during exploration traverses.

GEOSCIENCE AND GEOLOGIC HISTORY

Geologic goals

1. Develop and test a geological model of the current surface and interior.

2. Use the geological model to identify resources which are necessary or useful to support a human presence on Mars.

3. Identify and understand the internal and surface processes which have been active throughout the planet's history.

4. Establish a time frame for the occurrence of events in the planet's history.

Key issues to be addressed:

1. What is Mars like now?
    - Dimensions and composition of crust, mantle and core
    - Distribution, type and age of different rock exposed at the surface
    - Sites of present volcanic and tectonic activity

2. How did Mars form, and how did its mode of formation compare with the Earth's?
    - Materials from which Mars formed
    - Accretional history
    - Timing and nature of differentiation into crust, mantle and core

3. How did Mars evolve to its present state?
    - Impact history
    - Volcanic history
    - Deformational history and contrast with plate tectonics
    - Erosion and sedimentation history, with special reference to the action of water and ice, atmospheric composition and variation

GEOSCIENCE AND GEOLOGIC HISTORY

The study of the geologic history of Mars plays a key role in the scientific themes outlined above: the Evolution of Planets and Life and the Habitability of Mars. The major geoscience goals of Mars exploration are listed on the facing page. The sequence of Mars exploration, from precursor to human exploration phases, will help to develop and verify, at progressively finer levels of detail, a geological model of Mars. In addition to focusing our scientific understanding of the planet, the geologic model can be used in a predictive way to help insure mission safety and to help identify resources necessary to support human presence.

The key issues to be addressed concern understanding the present state of Mars, its formation, and how it evolved over time. Many of the geologic processes that have operated on Earth have also operated on Mars. Like the Earth, Mars is differentiated into crust, mantle and core. It has had a long history of volcanic and tectonic activity, and its surface has been sculpted by wind, water and ice. Yet the differences between the two planets are profound. We wish to understand the present configuration of the planet, what geologic geophysical and atmospheric processes are operating and have operated on the planet in the past, what is the history of their action, and why Earth and Mars are at present so geologically distinct.

GEOSCIENCE AND GEOLOGIC HISTORY

Precursor Phase

Earth-based observations
- Spectroscopy to determine mineralogy and search for evaporites and carbonates
- Observations of dust storms to determine where dust is deposited

Orbital Observations (Global Scale)
- Imaging: 10 m resolution globally, selected sites at <1 m res.
- Study and map geomorphological features
- Determine trafficability, surface roughness
- Map topography
- Determine mineralogical composition of surface
- Determine location and abundance of evaporites
- Determine geographic distribution of subsurface ice

Network Science
- Establish seismic network
- Chemical/mineralogical analysis of globally distributed sites
- Magnetic field at surface
- Deposit instruments in a dust storm center, e.g.
  - dust detector
  - flux detector
  - velocity-meter

Rover/Science
- Detailed chemistry/mineralogy of different rock types
- Close up view of different terrains
- Physical and chemical properties of soils
- Subsurface profiles (seismic, EM sounding, neutron spectrometer)
- Trafficability

Sample Return
- Samples of intrusive, extrusive, impact breccia, sediments, metamorphic rocks, æolian deposits, volatiles and soils
  - absolute ages
  - isotopes

GEOSCIENCE AND GEOLOGIC HISTORY

Precursor Phase

The main goal of this phase is to collect as much data as possible in order to understand Mars' geology so that sites can be picked for human exploration that satisfy both engineering needs to safely deliver and sustain humans at Mars and science needs to send humans to locations where the most critical science issues can be addressed. From this data base, a global geologic model of how Mars formed and evolved will be developed. Initially, the data base will be largely remote sensing data. Subsequently the model will be refined and either validated or changed by acquiring ground truth. This will be accomplished by progressively more complex missions such as network science and rover/sample return missions. The key objectives of precursor science is shown on the facing page, ordered by the type of observational platform.

Earth-based
Specific areas suggested for precursor study include: Earth-based observations of dust storms to determine implications of such storms (for example, attempt to determine where dust might be deposited to prevent building the base in an area doomed to be covered by 20 feet of dust). Ground-based spectroscopy of Mars yields useful information about surface mineralogy and hydrology over larger spatial scales.

Orbital
Orbital data will help to identify geological and topographical features as well as determine mineralogy and state and distribution of water on small spatial scales. This information will help to select landing and sampling sites, assess landing site hazards, recognize and interpret the origin of surface processes, and identify resources.

Network Science
Penetrators can be used to understand the composition of the martian surface and subsurface (vertical extent and uniformity of deposits, map vertical changes in subsurface composition, understand soil chemistries, look for hydrated minerals and permafrost). They could also be dropped into a dust storm to study the environmental conditions existing in such storms which may impact human operations on Mars.

Rover / Sample Return
Rovers can yield detailed information about the surface including a close-up view of different terrains, the physical and chemical properties of soils, the trafficability of the region, and can perform subsurface sounding. We need to acquire a variety of surface and subsurface samples to aid in understanding the formation and history of Mars, to verify ages associated with units, to provide ground truth to the orbital spectroscopic data, to verify that SNC meteorites are from Mars, to attempt to understand the environmental and volcanic histories, weathering dynamics, changes in atmospheric composition over time, and the possibility of life once existing on Mars. These samples would include crustal rocks from orbitally well characterized geologic units such as intrusive, extrusive, and metamorphic rocks, impact breccia, and sediments and subsurface deposits including soils, aeolian material, glacial till, volatile deposits and fresh, unoxidized rocks.

GEOSCIENCE AND GEOLOGIC HISTORY

Emplacement Phase

Activity	Motive	Tools
• Human survey of 10km surrounding area	Understand local field relations and geologic history	• Camera • Clinometer • Range finder
• Rover survey and sample collection from 100km area	Sample collection and field mapping of larger area than humans can access	• Give rovers similar analytic equipment to humans
• Collect samples with supporting photographs • Cleave rocks to expose fresh samples • Auger holes in rocks and collect materials • Trenching for soil profiles • Rake and sieve for samples • Subsurface drilling	Select and characterize best samples for return to Earth	• Hammer • Auger • Rake • Sieve • Drill • Hand lense • pH, Eh equipment • Hardness kit • Magnet • DSC/GC • Spectrometers • X-ray diffractometer
• Active seismic survey • Electomagnetic sounding	Look for water (deep surface drilling will not be possible in this phase)	• Seismometers • Radar sounding equipment • Radiation monitor • Magnetometor
• Engineering test of soil resource use	Test bearing strength of materials, test resource utilization strategies	

GEOSCIENCE AND GEOLOGIC HISTORY

Emplacement Phase

In this phase, humans are only on the surface for a short time. Thus, most effort should be directed toward collecting a diverse sample set for Earth-return. In order to select and characterize samples best suited to answer the pertinent scientific and engineering questions, the crew must establish an understanding of the local geological history and field relationships. Therefore, the crew will survey and collect samples from the local area (approximately 10 km diameter circle) surrounding the lander and teleoperate rovers to survey and collect samples from the surrounding 100 km region. Only small, hand-held analysis equipment will be used to help select the best samples to return to Earth for detailed analysis. At this stage, it will not be possible to bring enough equipment to drill into the deep subsurface, although shallow rock cores could be used to sample to depths of several centimeters. Active seismic techniques and electromagnetic sounding will be used to probe the subsurface to look for ice, permafrost and other useful resources. In addition to field science, engineering tests of resource utilization procedures using the soil or surface materials will be performed.

GEOSCIENCE AND GEOLOGIC HISTORY

Consolidation Phase

Activity	Equipment
• Thorough human survey of region within a two week field trip of base site (~100 km range) - Sample analysis for selection purposes (capability similar to human crews in emplacement phase) - Sample collection for return to base for more detailed analysis	Pressurized manned rover
• Survey by teleoperated rovers of interesting areas within 1000km of base area	Teleoperated rovers
• Search for and collect exotic, unique and critical samples, e.g; mantle zenoliths • Expand knowledge of resources - ore bodies - water bodies • Stratigraphic analysis of pre-cut area or drilled core - exobiology implications • Search for and investigate unique environmental niches - hydrothermal vents - permafrost/soil interface • Understand geomorphological environment on regional and local scales	Analytic facility (petrographic capability, electron microscopy, chemistry and mineralogy analysis capability EM sounding, active seismic)
• Drill to look for subsurface water ice • Drill to examine vertical structure of geologic units	Deep drilling capability (1km)

GEOSCIENCE AND GEOLOGIC HISTORY

Consolidation Phase

In this phase humans will be on the surface for extended periods. They will be capable of field trips of several weeks duration using a pressurized manned rover. Thus they will collect samples and survey regions previously investigated only by teleoperated rovers during the emplacement phase of exploration. The field expeditions will need basic sample analysis capability, similar to the tools listed on page 31, to help select the best samples for return to the base. Humans will also be able to survey interesting areas within a 3000 km range from the base using a suite of teleoperated rovers supported by a geosynchronous satellite. A basic rock laboratory, set up at the central base site, is required so that the scientist/astronauts can acquire new analytical data while at the planet and adapt their subsequent science strategy accordingly. The lab will require capability of doing petrography, mineralogy, major and minor element chemistry, scanning electron microscopy, volatile analysis, and spectroscopy. Some traverse geophysics capability will also be required (EM sounding, active seismicity). However, the main intent will still be screening accessible materials so that an optimum sample set can be returned to Earth for comprehensive analysis. Additionally, the crews will look for exotic samples (for example, mantle xenoliths, which would provide insight into the interior of the planet and the history of differentiation of Mars) and unique environmental niches (such as hydrothermal vent areas, areas at the permafrost/soil interface, etc.). At this stage, field activities will expand the knowledge of resources including assessing ore and water bodies. Also, they will expand the knowledge of local and regional geology using field mapping, stratigraphic analysis, geomorphologic analysis, glacial stratigraphic analysis (one of the most sensitive indicators of environmental history) and shallow drilling in sediments.

GEOSCIENCE AND GEOLOGIC HISTORY

Utilization Phase

- Global scale field mapping by human crews
  - establish remote outposts

- Explore relatively inaccessible but interesting areas
  - deep canyons
  - crater floors
  - polar caps
  - dune fields
  - lava flows
  - caldera regions
  - exobiology sites
  - present spring sites
  - ancient spring sites

- Drilling and mining
  - volatile and mineral resource development
  - geothermal energy (if possible)

- Address questions raised during previous phases

GEOSCIENCE AND GEOLOGIC HISTORY

Utilization Phase

At this point in time there should be enough data on the local and regional levels to produce a global map of the planet in some detail. Crews will now have the capability for field trips to virtually any place on the planet using suborbital rocket-powered vehicles and thus will investigate previously inaccessible/interesting places such as: potential exobiology sites (hot springs, geothermal vents), the polar regions, layered terrains, the bottoms of craters, the calderas of volcanoes, the bottoms of canyons, dune fields, and lava flows. At this time, the technology necessary for drilling should be available, so drilling and mining for a variety of purposes (such as building, farming, resource gathering) will be possible. Crews can investigate the possibility of using geothermal energy from active volcanic areas (if found). In the utilization phase, questions raised during previous phases can be answered and sites can be revisited for further observation.

III. HUMAN HABITABILITY

HABITABILITY STUDIES

One of the two overarching themes identified at the workshop on Mars Human Exploration Science was the habitability of Mars for humans. This theme investigates the adaptability of humans to the conditions on Mars and the availability of resources on Mars to support life.

Human adaptability to Mars was not considered in this report but would deal with both medical issues as well as issues dealing with human factors: e.g., perception, behavior, and performance in the Mars Base environment.

The use of Mars resources to support humans on the surface is a key part of this report. The identification of Mars resources to support human activities begins in the precursor phase and must include Earth-based research to test resource extraction concepts. The importance of this can be illustrated by the case of water. Water has been identified in the atmosphere and polar caps of Mars. Water is believed to exist in the soil in the form of hydrated minerals and possibly permafrost in the polar latitudes. Assessing the availability of water may be an important part of planning for a Mars base. The best way to obtain water is an engineering question which must be traded off against other constraints. Atmospheric water may be technically difficult to extract but is ubiquitous. Soil water of hydration may be abundant but may pose problems of handling feedstock and tailings. Permafrost water and polar ice may place undesired restrictions on the latitude of the base while still presenting problems with material handling. Ground-based research may help provide the information to make these tradeoffs.

An important part of the Mars habitability theme is the understanding of how living organisms can survive on Mars, both as part of enclosed life support and agriculture systems and exposed to the harsh environment. After the establishment of a permanent base, the question of the human habitability of Mars becomes a global question centered on the ability of the planet to support a habitable environment and how this environment is protected and maintained.

HABITABILITY STUDIES

Phase	Notes
Precursor	• assessment of global volatiles and minerals • assessment of construction possibilities and architectural design
Emplacement	• verification of resource and extraction tests • studies of human behavior and medical environmental adaptation
Consolidation	• extraction of resources • habitat construction • regional scale resource survey • mature life support system with bioregenerative system tied to Mars resources • develop agriculture in close environments based on available materials
Utilization	• field tests of organisms adapted to Mars • studies of human behavior, medical and environment studies on extended stays • global resource survey • small scale studies of engineering techniques for climate alteration on Mars • controlled release of genetically altered organisms • detailed environmental monitoring and alteration studies

MARTIAN RESOURCES

Relevant resources on Mars include:

- **Water**
- **Volatiles needed for life support, consumables and fuels**
- **Suitable construction and insulating materials**
- **Useful topographic features**
- **Energy supply**
- **Accessible source of ores bearing useful amounts of K, Ca, N, S, Na, P, Si, Al, Fe, Mg, Ti.**

MARTIAN RESOURCES

Mars has many, if not all, of the resources in some accessible form that will be needed to sustain humans on the surface. By using local resources, operations on Mars will become independent from Earth-based supply lines. The most important resources on Mars are given on the preceding page.

Water will be a key resource for Mars exploration. Water is important for human consumption and for growing plants as well as a convenient source of hydrogen which is a component of most fuels, fertilizers, and manufactured substances. Water is available in small quantities in the atmosphere, surface soils contain a few weight percent of adsorbed water, the permanent polar caps are water ice, and water may occur underground as permafrost or in deep subsurface aquifers. Assessing the location and accessibility of water sources will be an important science objective of Mars exploration in all phases.

In addition to water, other volatiles will be needed for life support consumables and fuels. Oxygen and Nitrogen will be particularly important in this respect.

Suitable materials that can be used in construction of habitats and other buildings and for insulation and radiation shielding should be available near human bases. Unconsolidated powder-sized, sand-sized, and gravel-sized material will be useful. Energy self sufficiency may be difficult to achieve on Mars and much work is needed to evaluate martian energy resources. Solar and wind energy can plausibly be utilized.

Eventually, martian minerals could be mined and smelted to supply structural components or to fabricate materials..

Precursor Phase Resource Assessment

Water	Mission Type
1. Atmosphere	
• Assess interannual and spatial variation of atmospheric water	Orbiter
• Assess sources and sinks	Orbiter
• Assess diurnal cycle, condensation and frost	Orbiter, Landed Vehicle
• Design and laboratory test of atmospheric gas extraction technology	Earth-based studies
2. Soil (adsorbed and hydration water)	
• Assess global distribution of near-surface water	Orbiter, Landed Vehicle
• Assess amount of water in soils	Landed Vehicle, Sample Return
• Assess energy requirements to extract water from soils	Landed Vehicle, Sample Return
• Design of engineering systems for processing and extracting water from soils	Earth-based studies
3. Permafrost	
• Assess existence, depth, and geographic distribution	Orbiter, Landed Vehicle
• Design engineering system for extracting water	Earth-based studies
4. Polar Caps	
• Assess the thickness of polar caps	Orbiter, Landed Vehicle
• Determine whether there is a subpolar aquifer of liquid water	Orbiter, Landed Vehicle
5. Other, e.g. hydrothermal vents, surface brine solutions, etc.	
• Search for heretofore undetected sources of water	Orbiter, Landed Vehicle

PRECURSOR PHASE RESOURCE ASSESMENT

Insulating and Building Materials	Mission Type
• Locate potential base sites with accessible sources of insulating and construction materials	Orbiter, Landed Vehicle
• Locate potential base sites with potentially useful topographic features (e.g. caves)	Orbiter, Landed Vehicle
• Engineering design and field tests of habitat construction making use of local materials	Earth-based studies
Energy Source	
• Global search for evidence of hydrothermal activity	Orbiter
• Determine near surface wind regime at base site and assess viability as an energy source	Landed Vehicle, Earth-based studies
• Assess viability of solar energy for use on Mars	Earth-based studies
Metal Ores	
• Global elemental and mineralogical characterization of the surface	Orbiter
• Surface chemistry and mineralogy of selected sites	Landed Vehicle, Sample Return

EMPLACEMENT PHASE RESOURCE ASSESSMENT

- Verify understanding of local resources (based on precursor missions)

- Survey local area to determine state and distribution of volatiles, especially water

- Experimental test and prototype deployment of water extraction technology

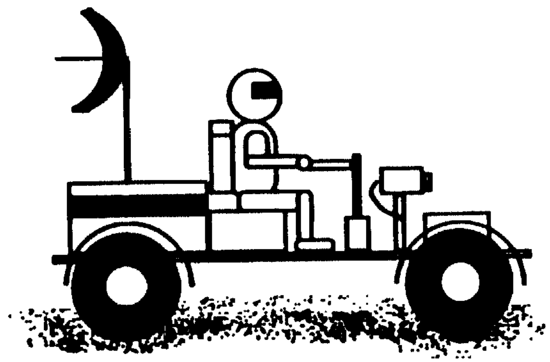
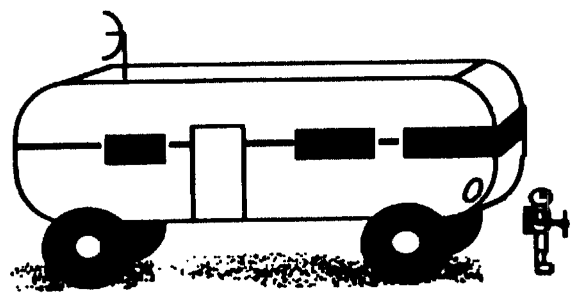
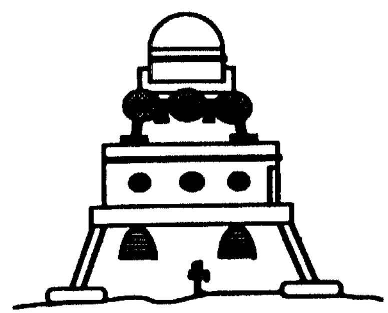
- Experimental test and prototype deployment of volatile extraction from Mars atmospheric gases

- Prospecting: Collect samples which may contain useful minerals for Earth return.

EMPLACEMENT PHASE RESOURCE ASSESSMENT

Using martian resources to sustain humans on the surface of Mars will greatly enhance the mission capabilities while decreasing the cost of transporting consumables from Earth. The exploration objectives related to resources that will be a focus of the emplacement phase of Mars exploration are listed on the preceding page. A mature resource use capability will evolve during the consolidation and utilization phases.

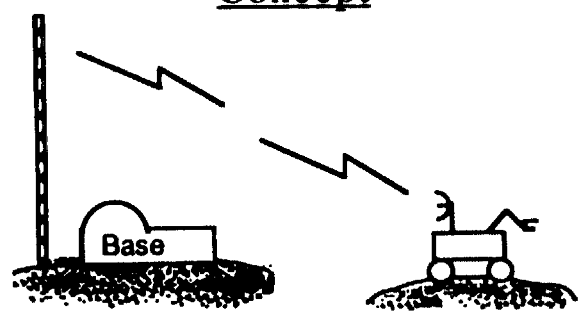
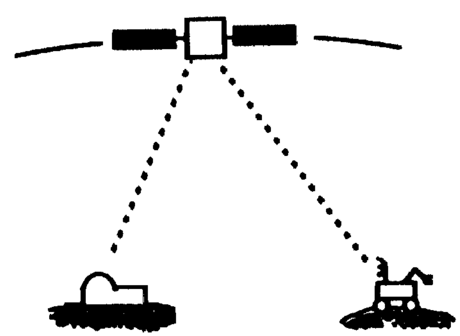
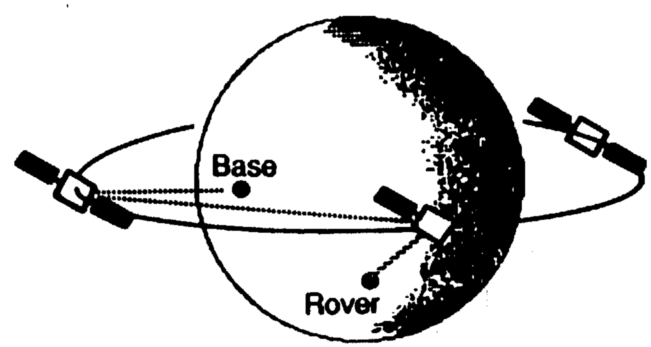
MOBILITY IN HUMAN EXPLORATION OF MARS

Phase	Concept	Range
Emplacement		Minimal Rover Range: 8 hours
Consolidation		Pressurized all terrain vehicle Range: 2 weeks
Utilization		Suborbital rocket with habitat, lab and ascent vehicle Range: 90 days

MOBILITY

The preceding figure shows the three phases of human mobility envisioned for Mars. During the first phase (emplacement) humans are limited to small, light, open air rovers. These rovers are capable of up to 8 hours of travel. The rovers' travel time is limited by the capability of the life support system on a space suit. In the second phase (consolidation) humans will have a large pressurized mobile research vehicle with a shirt sleeve life support system. People will be able to survive in the vehicle for up to two weeks. In the final phase (utilization) humans will have powerful suborbital rockets capable of reaching any point on Mars. These rockets will be very similar to the landing craft from the first explorations of Mars.

TELEOPERATION IN HUMAN EXPLORATION OF MARS

Phase	Concept	Notes
Emplacement		• ~100 km range • line of site communication form surface antenna
Consolidation		• several with ~100 km range • e.g., explore areas within Coprates Quadrangle as shown in Figure 1. • communication via aerostationary satellite
Utilization		• entire planet covered • augmented by sample return to base for analysis • communication via network of aerostationary satellites

TELEPRESENCE

This figure illustrates the use of teleoperated vehicles during the human exploration of Mars. In the top panel, which represents the emplacement phase, a local communication capability allows for the control of rovers over further distances (~100 km) than humans are likely to be able to reach. In the consolidation phase, the emplacement of a synchronous relay satellite over the base allows for teleoperation of vehicles located anywhere within the satellite footprint on Mars. In the utilization phase, the base has evolved into a permanent station. At this point, a global network of communications satellites allows for teleoperation and telepresence anywhere on or around the planet.

IV. CONCLUSIONS

- We have identified two major themes for exploration of Mars
  - Planetary evolution and life
  - Human habitability of Mars
- Understanding the evolution of the Mars environment and how it relates to the search for life will be a major science driver
- Determining the long-term habitability of Mars will be a key focus of Mars exploration
- Four major phases of exploration were identified
  - Precursor: prior to human landings
  - Emplacement: first human landings
  - Consolidation: establishment of a outpost
  - Utilization: exploration from a permanent outpost
- The activities during each phase and the extent of exploration will be determined by the mobility range of human-occupied and teleoperated rovers.
- We have identified a geographical area that could be the focus of Mars exploration activities in the first 3 phases
- Human exploration of Mars will involve a mix of direct human involvement and teleoperation/telepresence.
- Science objectives for Mars exploration need to be formulated within 50 year time frames
- The precursor science program should be designed to support the focus and capabilities of human operations on the surface of Mars.

RECOMMENDATIONS

- The role of the lunar base in developing plans for exploration of Mars needs to be defined and critically examined. Mars programs should consider and use the Lunar outpost as a Mars testbed.

- Instrument and experiment concepts for Mars precursors must be developed.

- Perform detailed studies to select sites for human landings within the geographical area defined on page 5.

- Engineering studies of resource utilization technologies are needed.

- Further definition of role of teleoperation/telepresence in human exploration is needed to determine how robotic presence can aid human exploration. In particular, penetrator capabilities/technologies should be addressed.

- Teleoperation and other field techniques need to be developed and tested in Mars-analog terrestrial environments (e.g. Antarctica).

- Design and test advanced human mobility concepts.

LIST OF PARTICIPANTS

Albee, Arden	Cal. Tech.
Anderson, Dale	Lockheed, NASA-HQ
Barlow, Nadine	Lunar & Planetary Inst.
Beckman, John	NASA JPL
Bell, Jerry	NASA JSC
Blanchard, Doug	NASA JSC
Boain, Ronald	NASA JPL
Bohlin, David	NASA HQ
Bourke, Roger	NASA JPL
Boyce, Joseph	NASA HQ
Brace, Larry	NASA GSFC
Briggs, Geoffrey	NASA HQ
Budden, Nancy Ann	NASA JSC
Budney, Charles	NASA JPL
Carr, Michael	US Geological Survey
Clark, Benton	Martin Marietta
Cunningham, Glenn	NASA JPL
Davis, Wanda	NASA NASA ARC
DesMarais, David	NASA ARC
Devincenzi, Don	NASA ARC
Duke, Michael	NASA JSC
Golombek, Mathew	NASA JPL
Gooding, James	NASA JSC
Greeley, Ronald	Arizona state U.
Gwynne, Owen	NASA ARC
Haberle, Robert	NASA ARC
Jakosky, Bruce	U. of Colorado
Kahn, Ralph	NASA JPL
Kieffer, Hugh	US Geological Survey
Klein, Harold	Santa Clara U.
Kwok, Johnny	NASA JPL
Leovy, Conway	U. of Washington
Marshall, John	NASA ARC
McCleese, Dan	NASA JPL
McKay, Chris	NASA ARC
Mitchell, Robert	NASA JPL
Morrison, Don	NASA JSC
Muirhead, Brian	NASA JPL
Murray, Bruce	Cal. Tech.
Nash, Douglas	NASA JPL
Niehoff, John	SAIC
Olhoeft, Gary	US Geological Survey
Owen, Tobias	State U.of New York
Penn, Thomas	NASA JPL
Pepin, Robert	Univ. Minn
Pilcher, Carl	NASA HQ
Pivirotto, Donna	NASA JPL
Plescia, Jeff	NASA JPL
Randolph, James	NASA JPL
Rea, Don	NASA JPL
Roush, Ted	NASA ARC
Rummel, John	NASA HQ
Smith, Dave	NASA JSC
Snyder, Gerald	NASA JPL
Squyres, Steve	Cornell Univ.
Stoker, Carol	NASA ARC
Suess, Steve	NASA MSFC
Wallace, Richard	NASA JPL
Wharton, Robert	University of Nevada, Renc
Young, Richard	NASA ARC
Zent, Aaron	NASA ARC
Zurek, Richard	NASA JPL